Measuring the Primordial Deuterium Abundance During the Cosmic Dark Ages

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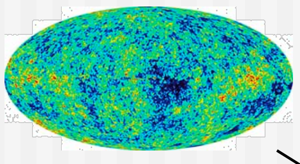
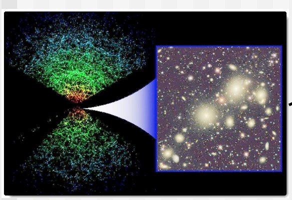
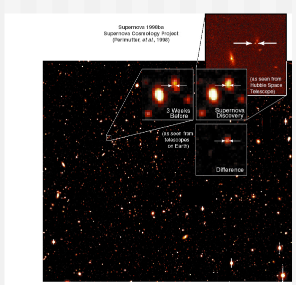
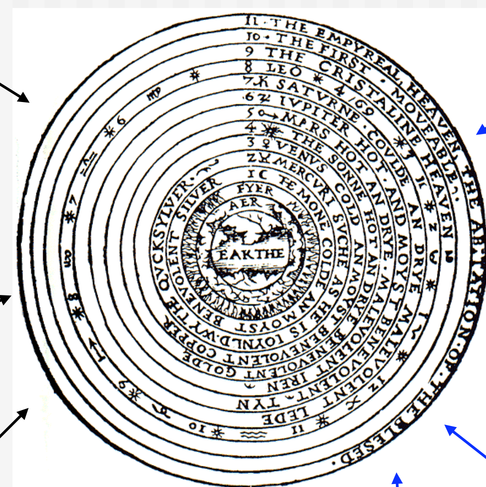
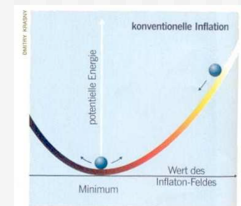
Standard Model of the Universe

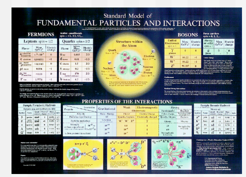


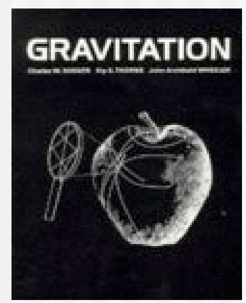


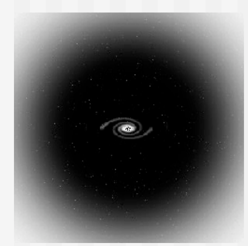












Λ = "lambda"

Standard Model of the Universe
Potential Ways Forward

Physical Theory

New physical theories that give
more refined or alternate predictions

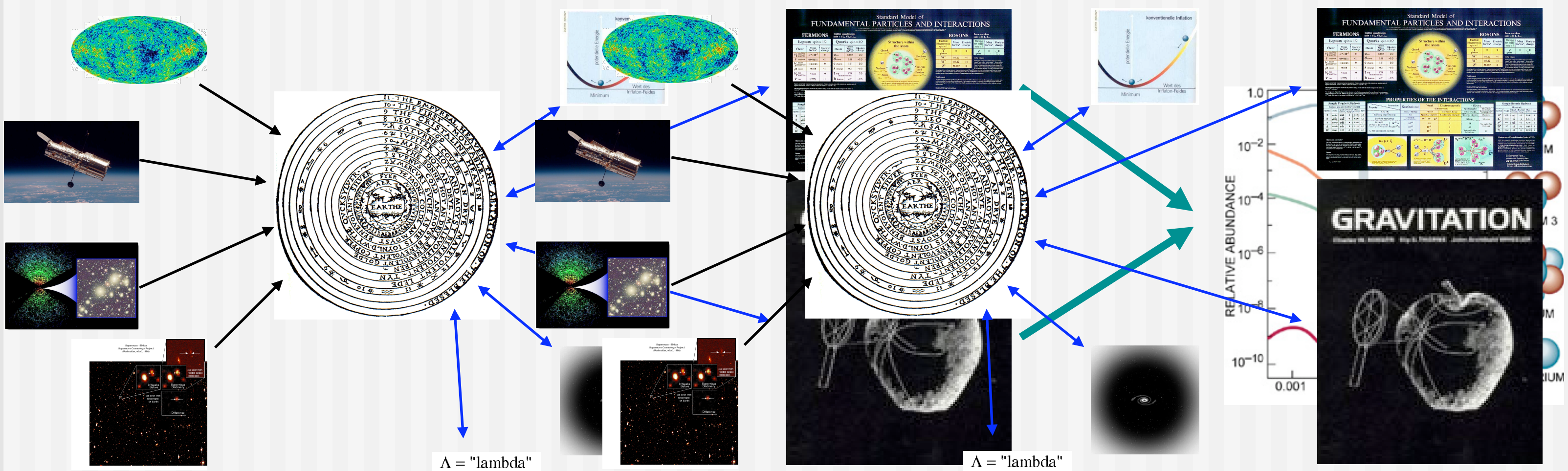
New theoretical signatures and probes of
the standard cosmological model

New and perhaps unexpected revelations
from experiment and observation

Cosmological
Observation

Standard Model of the Universe

GR + SU(3)xSU(2)xU(1) $\longrightarrow$ BBN

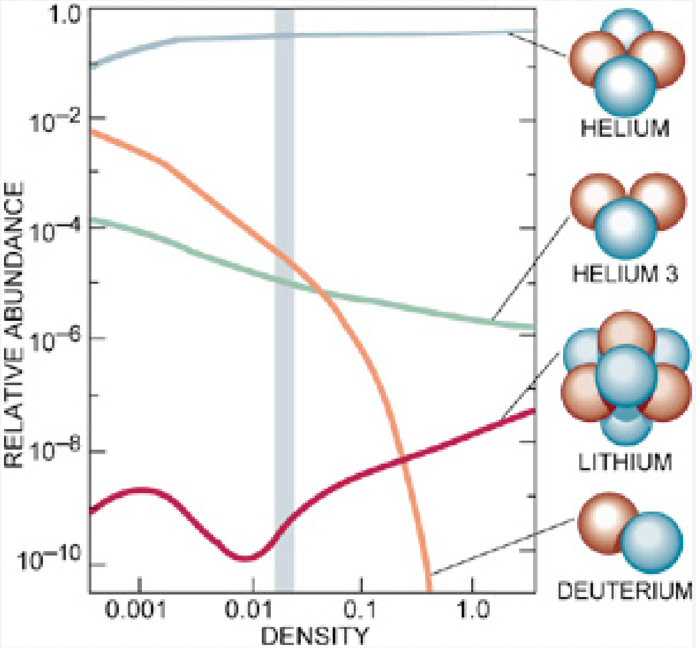


Big Bang Nucleosynthesis
l'école de Chicago

- Relative abundance of light elements can be calculated reliably using GR and nuclear physics.

- In the standard model only one free parameter

$$\eta = n_{\rm b}/s$$



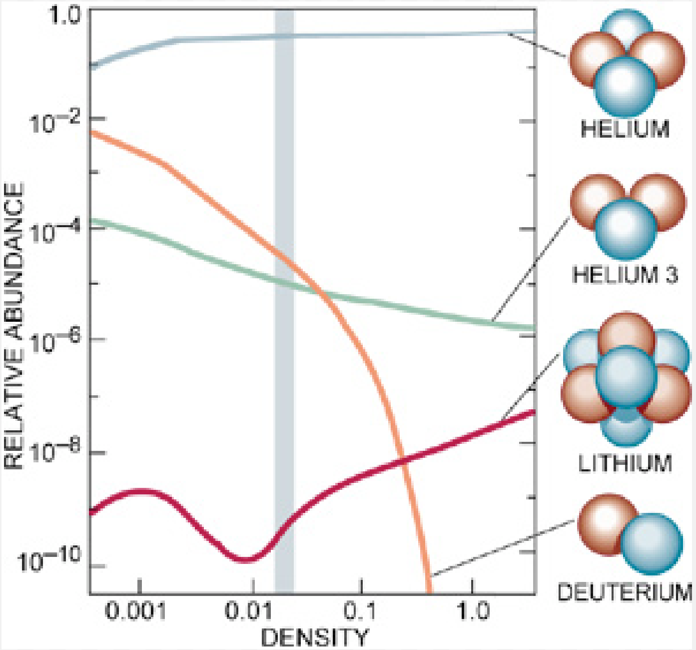
- Look for non standard model physics!

Big Bang Nucleosynthesis
Deuteronomy

- Deuterium: The Baryonometer
- Why is it interesting?
- Primordial abundance $[\mathrm{D/H}]$ most sensitive to

$$\eta = n_{\mathrm{b}}/s\,.$$

$$\Omega_{\mathrm{b}} h^2$$

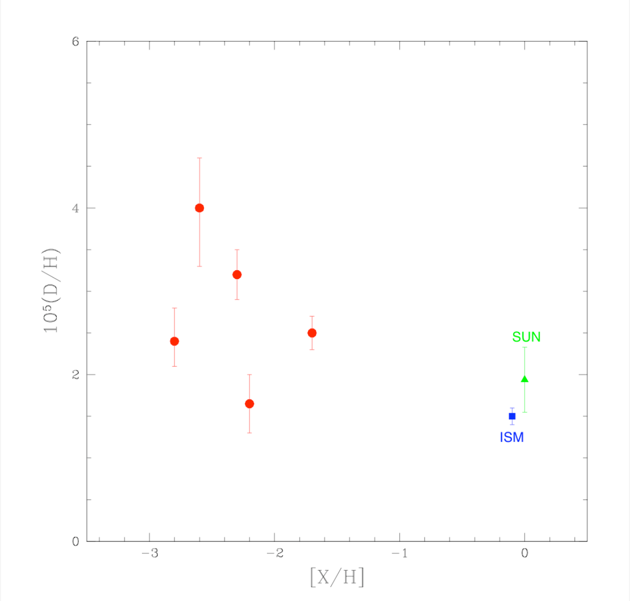


The Deuterium Abundance
Just measure it!

- How can we measure primordial $[\mathrm{D/H}]$?
- D gets destroyed in stars and galaxies *(Reeves et al. 1973).* Want a pristine environment.
- QSO Absorption Line systems that appear to have low star-formation.

But… $\chi^2 \gtrsim 16$

For 5 data points!



Credit: Gary Steigman

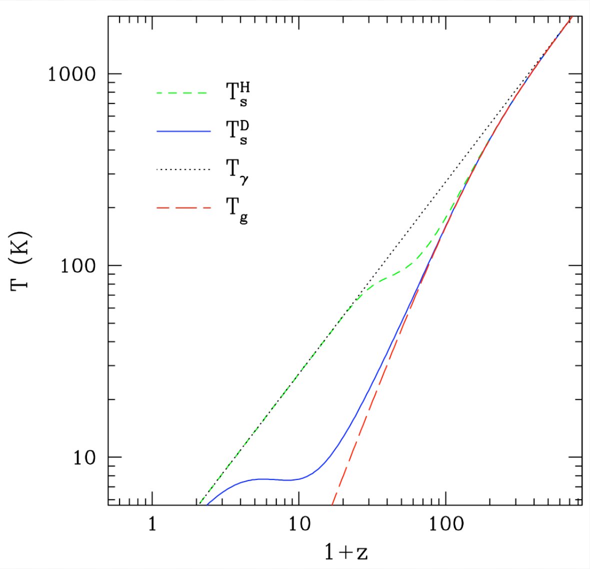
The Primordial Deuterium Abundance
Measure early. Measure often.

- Cosmic Dark Ages: Neutral primordial medium after recombination before most stars and galaxies form. As pristine as it gets!
- Basic Concept: Cross-correlate measurements of brightness temperature fluctuations at $\lambda_{\rm D} = (1+z)\lambda_{92}$ with those at $\lambda_{\rm H} = (1+z)\lambda_{21}$.
- Defeat tiny $[\mathrm{D/H}]$ with statistics and enormous number of pixels.

KS and Steve Furlanetto: astro-ph/0505173

The Cosmic Dark Ages

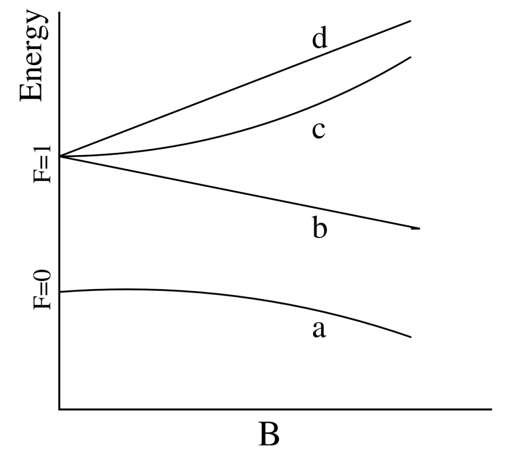
Cosmic Dark Ages: At $z \sim 200$ the gas temperature drops below the CMB temperature.



Atomic Physics: Hyperfine Splitting
Hydrogen vs. Deuterium

- The $\boldsymbol{\mu} \cdot \mathbf{B}$ interaction splits the ground state of single-electron atoms into eigenstates of the total spin operator $\mathbf{F} = \mathbf{S}+\mathbf{I}$ with eigenvalues $F_+ = I + 1/2$ and $F_- = I - 1/2$.

$$\Delta E = (16/3) F_+ \mu_B (g_N \mu_N / a_0^3)$$



Hydrogen: $F_+ = 1$ $F_- = 0$

Deuterium: $F_+ = 3/2$ $F_- = 1/2$

Atomic Physics: The Spin Temperature
Hydrogen vs. Deuterium

- The Spin-Temperature

$$n_+/n_- = (g_+/g_-)\exp\{-T_\star/T_\mathrm{s}\}$$

$$(g_+^\mathrm{H}/g_-^\mathrm{H}) = 3 \qquad (g_+^\mathrm{D}/g_-^\mathrm{D}) = 2$$

$$T_\star^\mathrm{H} = 0.0682\ \mathrm{K} \qquad T_\star^\mathrm{D} = 0.0157\ \mathrm{K}$$

Spin Temperature Equilibrium
Collisions, WF, and the CMB

- In equilibrium:

$$T_{\rm s}^{\rm x} = \frac{(1+\chi^{\rm x})T_{\rm g}T_\gamma}{(T_{\rm g}+\chi^{\rm x}T_\gamma)}$$

where $$\chi^{\rm x} \equiv \chi_c^{\rm x} + \chi_\alpha^{\rm x}$$

(collisions) $$\chi_c^{\rm x} = (C_{+-}^{\rm x} T_\star^{\rm x})/(A_{+-}^{\rm x} T_\gamma)$$

(WF effect) $$\chi_\alpha^{\rm x} = (P_{+-}^{\rm x} T_\star^{\rm x})/(A_{+-}^{\rm x} T_\gamma)$$

Spin-Change Collisions
The Deuterium Cross Section

- Spin-change collision rate:

$$C^{\mathrm{X}}_{+-} = \bar{v}_{\mathrm{XH}}\bar{\sigma}^{\mathrm{XH}}_{+-}n_{\mathrm{H}}$$

- D-H Spin-change cross section

Triplet Phase Shift

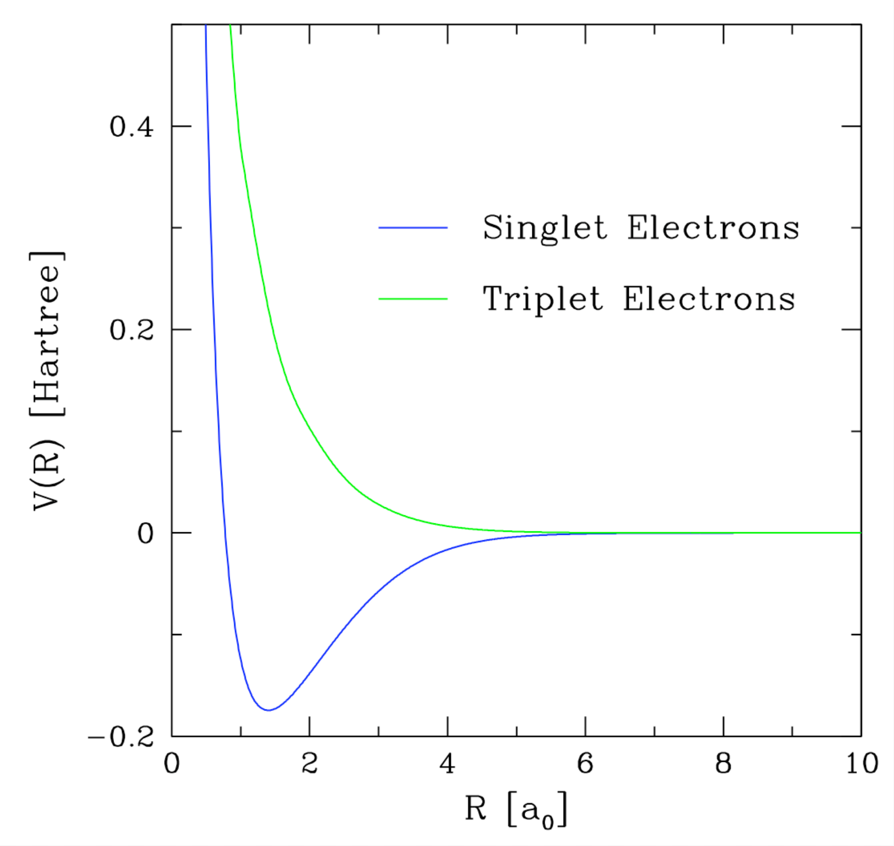
$$\sigma^{\mathrm{DH}}_{+-} = \frac{\pi}{3k^2}\sum_{l=0}^{\infty}(2l+1)\sin^2({}^{t}\eta^{\mathrm{DH}}_{l} - {}^{s}\eta^{\mathrm{DH}}_{l})$$

Singlet Phase Shift

Wavevector $k = \mu_{\mathrm{DH}}v/\hbar$

D-H Spin Change Cross Section
The Electronic Potentials

- The Potentials:



D-H Spin Change Cross Section
Solve the Schrödinger Equation

- Solving for phase shifts:

$$\left\{\frac{d^2}{dR^2} - \frac{l(l+1)}{R^2} + \frac{2\mu}{\hbar^2}\left[E - V(R)\right]\right\}\left[R\psi_l(R)\right] = 0$$

$$\lim_{R\to\infty} \psi_l(R) \approx R^{-1}\sin\left(kR - l\frac{\pi}{2} + \eta_l\right)$$

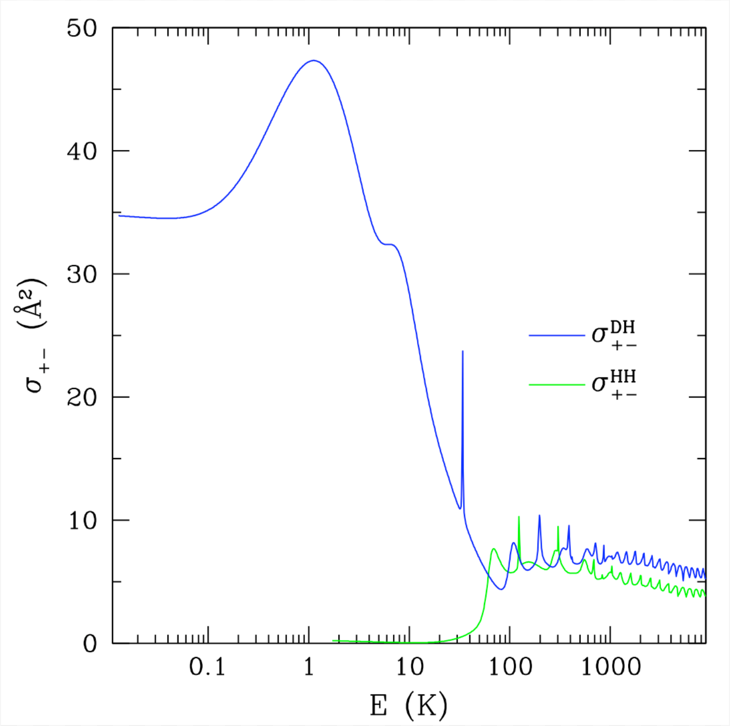
$$\sin\left(\eta_l - l\frac{\pi}{2}\right) = \frac{-2\mu}{\hbar^2 k}\int_0^\infty RdR\sin(kR)V(R)\psi_l(R)$$

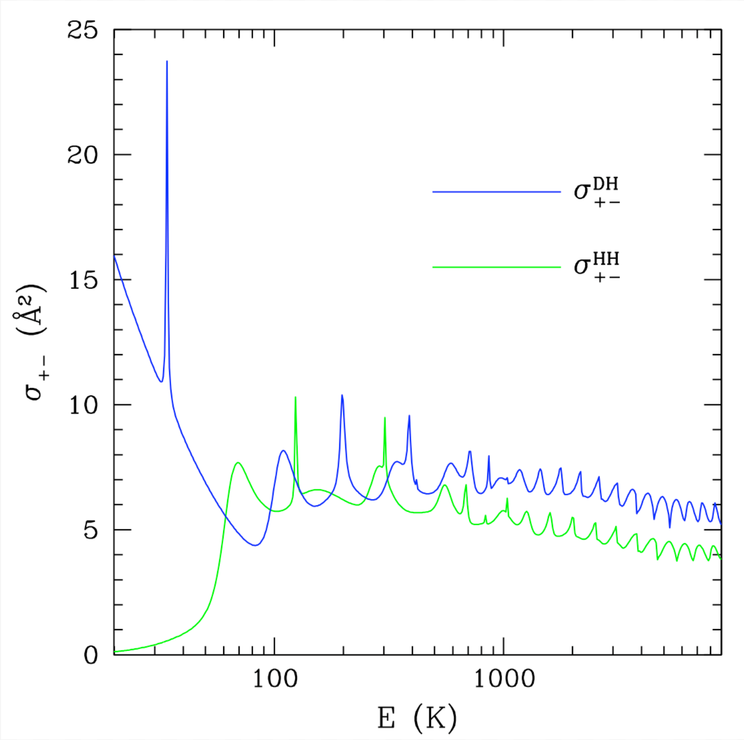
Asymptotic Angle Addition Formula

$$\cos\left(\eta_l - l\frac{\pi}{2}\right) = \frac{2\mu}{\hbar^2 k}\int_0^\infty RdR\cos(kR)V(R)\psi_l(R)$$

Spin Change Cross Sections
Hydrogen vs. Deuterium

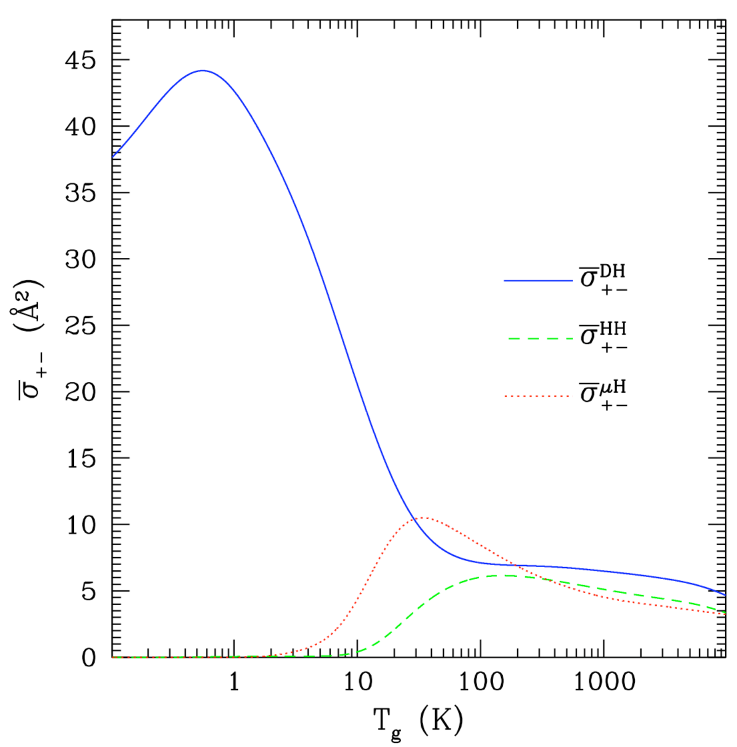
- Spin-change cross section:





Thermal Spin Change Cross Section
Hydrogen vs. Deuterium

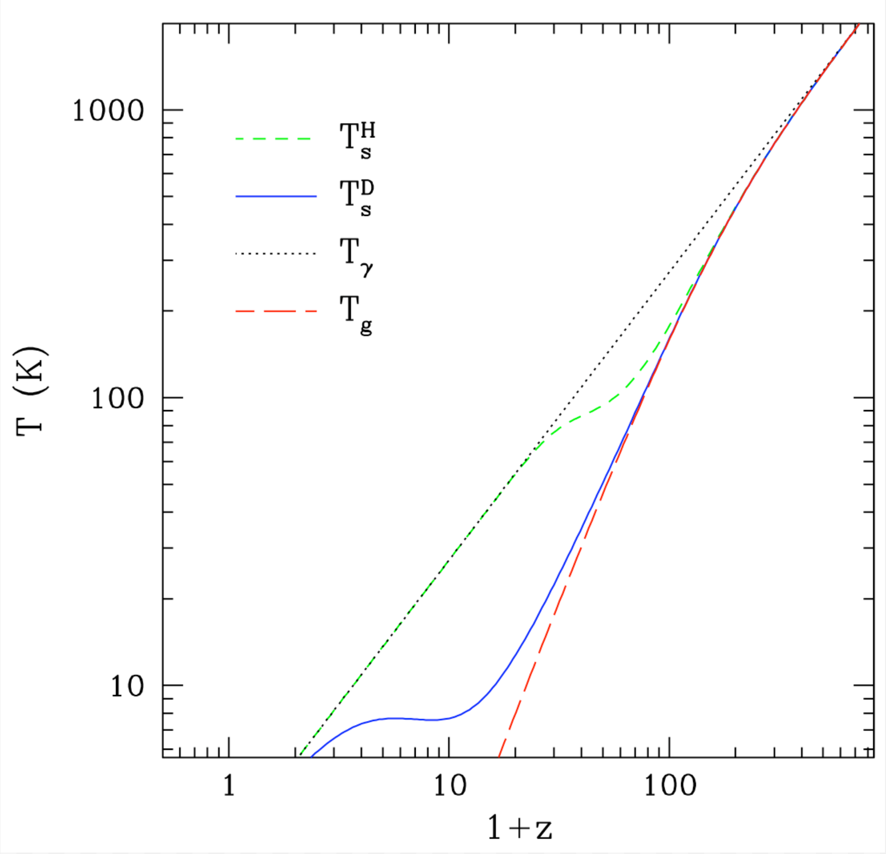
- Thermal Spin-change cross section



Spin Temperature Evolution
Hydrogen vs. Deuterium

- Spin Temperature Evolution

$$T_{\mathrm{s}}^{\mathrm{X}} = \frac{(1+\chi^{\mathrm{X}})T_{\mathrm{g}}T_{\gamma}}{(T_{\mathrm{g}}+\chi^{\mathrm{X}}T_{\gamma})}$$



The Brightness Temperature
Absorption or Emission

- The Brightness Temperature

Absorption or Emission with respect to the CMB

$$T_{\mathrm{b}}^{\mathrm{X}} = a\tau_{\mathrm{X}}(T_{\mathrm{s}}^{\mathrm{X}} - T_{\gamma})$$

$$\tau_{\mathrm{X}} = \frac{g_{+}^{\mathrm{X}} c\lambda^2 h A_{+-}^{\mathrm{X}} n_{\mathrm{X}}}{8(g_{+}^{\mathrm{X}} + g_{-}^{\mathrm{X}})\pi k_{\mathrm{B}} T_{\mathrm{s}}^{\mathrm{X}} \mathcal{H}(z)}$$

Difficult to observe 0^{th} order effect. T_b is of order 50mK vs. foreground noise at 10-1000K in the frequency range of interest.

Brightness Temperature Fluctuations

- Brightness Temperature Fluctuations

$$\delta^{\mathrm{X}}_{T_{\mathrm{b}}}(\hat{\mathbf{n}}, a) \equiv \delta T^{\mathrm{X}}_{\mathrm{b}}(\hat{\mathbf{n}}, a)/T^{\mathrm{X}}_{\mathrm{b}}(a) = \beta^{\mathrm{X}}_{T_{\mathrm{b}}}(a)\delta(\hat{\mathbf{n}}, a)$$

Function of z that depends on atomic physics
And Spin Temperature history

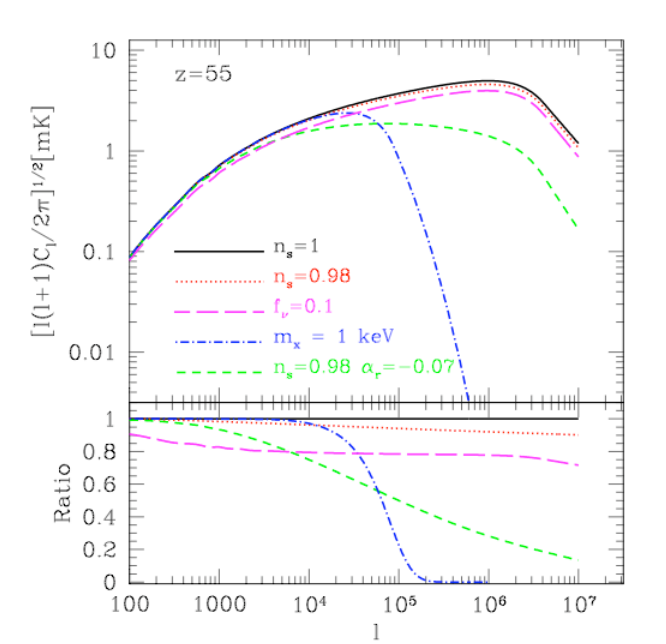
- Driven by Density Fluctuations

$$\delta(\hat{\mathbf{n}}, a) = \delta n_{\mathrm{H}}(\hat{\mathbf{n}}, a)/n_{\mathrm{H}}(a) = \delta n_{\mathrm{D}}(\hat{\mathbf{n}}, a)/n_{\mathrm{D}}(a)$$

Can observe fluctuations because noise/foregrounds are smooth in frequency space (the radial direction).

Brightness Temperature Fluctuations

Aside: Can use these fluctuations to probe the matter power spectrum



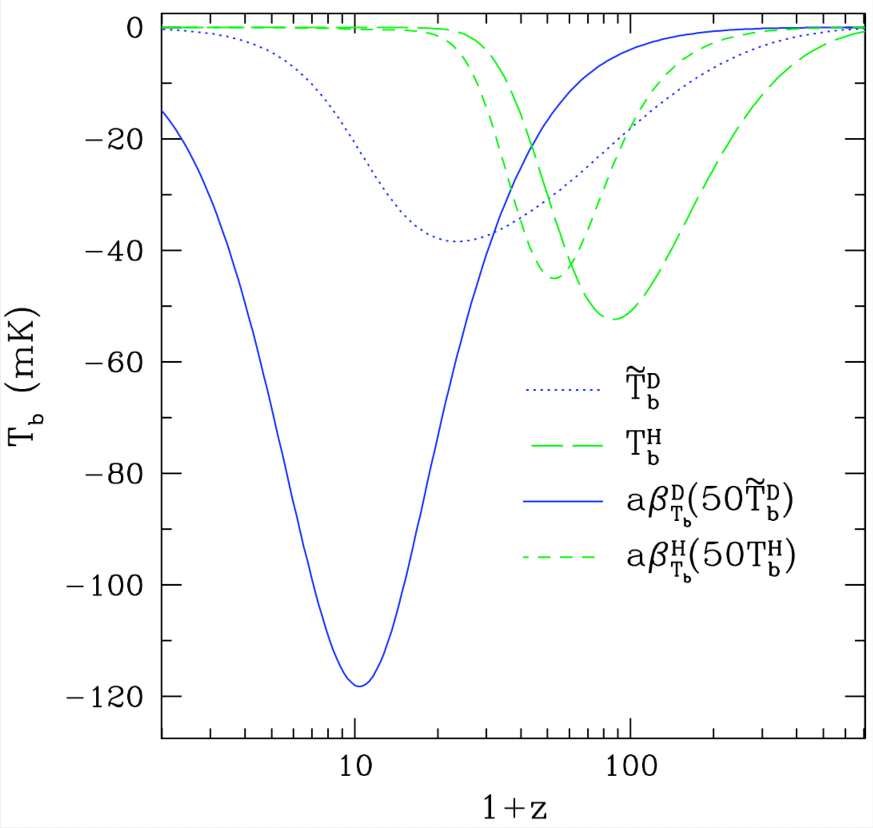
Loeb and Zaldarriaga 2004

Brightness Temperature Fluctuations

- Brightness Temperature Fluctuations

$$T_{\rm b}^{\rm D} \equiv \epsilon \widetilde{T}_{\rm b}^{\rm D}$$

$$\epsilon \equiv [{\rm D/H}]$$



The D-H Cross Correlation Signal

- D-H cross correlation

Zero mean Uncorrelated Random Fields

$$
\begin{aligned}
\mathcal{O}[\hat{\mathbf{n}};\nu] &= H(\hat{\mathbf{n}},\nu/\nu_{21}) + \epsilon D(\hat{\mathbf{n}},\nu/\nu_{92}) + N[\hat{\mathbf{n}};\nu] \\
H(\hat{\mathbf{n}},a) &= \beta^{\mathrm{H}}_{T_{\mathrm{b}}}(a) T^{\mathrm{H}}_{\mathrm{b}}(a)\delta(\hat{\mathbf{n}},a) \\
\epsilon D(\hat{\mathbf{n}},a) &= \epsilon \beta^{\mathrm{D}}_{T_{\mathrm{b}}}(a) \widetilde{T}^{\mathrm{D}}_{\mathrm{b}}(a)\delta(\hat{\mathbf{n}},a)
\end{aligned}
$$

Gaussian Noise

$$\langle \mathcal{O}[\hat{\mathbf{n}};\nu_\alpha]\mathcal{O}[\hat{\mathbf{n}};\nu_\beta]\rangle = \epsilon\langle H_\alpha D_\beta\rangle$$

$$H_\alpha \equiv H(\hat{\mathbf{n}},\nu_\alpha/\nu_{21})$$

$$D_\beta \equiv D(\hat{\mathbf{n}},\nu_\beta/\nu_{92})$$

$$\nu_\beta \equiv (\nu_{92}/\nu_{21})\nu_\alpha$$

$$N_\alpha = N[\hat{\mathbf{n}};\nu_\alpha]$$

The Bottom Line

- The Main Point:

The 21-cm and 92-cm fluctuations at these frequency separations must be correlated because they trace the same underlying patches of the Universe.

$$\langle \mathcal{O}[\hat{\mathbf{n}};\nu_\alpha]\mathcal{O}[\hat{\mathbf{n}};\nu_\beta]\rangle \;=\; \epsilon\langle H_\alpha D_\beta\rangle$$

when $$\nu_\beta \equiv (\nu_{92}/\nu_{21})\nu_\alpha$$

Signal to Noise Estimate

- In a given band

$$\boxed{\frac{\mathcal{S}}{\mathcal{N}}(\nu_\alpha) = \epsilon\frac{4}{\theta_\beta}\frac{\langle H_\alpha D_\beta\rangle}{\sqrt{(\langle H_\alpha^2\rangle + \langle N_\alpha^2\rangle)(\langle H_\beta^2\rangle + \langle N_\beta^2\rangle)}}}$$

$$\langle N_\alpha^2\rangle = T_{\rm sys}^2/(f_{\rm cov}^2\,\Delta\nu\,t_{\rm int})$$

$$T_{\rm sys} = 6500[\nu_\alpha/(30{\rm MHz})]^{-2}\ {\rm K}$$

$$\langle H_\alpha D_\beta\rangle = \sigma_\delta^2(\beta_{T_{\rm b}}^{\rm H}\,T_{\rm b}^{\rm H})(\beta_{T_b}^{\rm D}\,\widetilde{T}_{\rm b}^{\rm D})$$

$$\langle H_\alpha^2\rangle = \sigma_\delta^2(\beta_{T_{\rm b}}^{\rm H}\,T_{\rm b}^{\rm H})^2$$

$$\theta_\beta = \lambda_\beta/L$$

"Variance in coins"

$$\sigma_\delta^2 = \frac{2}{\pi^2}\int_0^\infty dk k P(k)\int_0^k dk_z j_0^2(\xi k_z\rho)\frac{J_1^2(\sqrt{k^2-k_z^2}\rho)}{(k^2-k_z^2)\rho^2}$$

Detectability of the Signal

- Detecting D/H:

$$[\mathrm{D}/\mathrm{H}] \sim 3 \times 10^{-5}$$

Detection at 1- to 2-σ *:* $L \sim 7.5\ \mathrm{km}$

If the heating is efficient prior to reionization: $L \sim 2.5\ \mathrm{km}$

A 21-cm experiment capable of mapping fluctuations out to $l_{max} \sim 10^5$ *could achieve a precision of 1% or better!*

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The End!